

# Rapid Development of Gossamer Propulsion for NASA Inner Solar System Science Missions

by  
Roy M. Young\* and Edward E. Montgomery IV†  
*NASA George C. Marshall Space Flight Center, Huntsville, AL 35812*

Over a two and one-half year period dating from 2003 through 2005, NASA's In-Space Propulsion Program matured solar sail technology from laboratory components to full systems, demonstrated in as relevant a space environment as could feasibly be simulated on the ground. This paper describes the challenges identified; as well as the approaches taken toward solving a broad set of issues spanning material science, manufacturing technology, and interplanetary trajectory optimization. Revolutionary advances in system structural predictive analysis and characterization testing occurred. Also addressed are the remaining technology challenges that might be resolved with further ground technology research, geared toward reducing technical risks associated with future space validation and science missions.

## I. Introduction

NASA's In-Space Propulsion Technology (ISPT) Program is investing in technologies that have the potential to revolutionize the robotic exploration of deep space. For robotic exploration and science missions, increased efficiencies of future propulsion systems are critical to reduce overall life-cycle costs and, in some cases, enable missions previously considered impossible. Continued reliance on conventional chemical propulsion alone will not enable the robust exploration of deep space - the maximum theoretical efficiencies have almost been reached and they are insufficient to meet needs for many ambitious science missions currently being considered. The ISPT Program is developing technologies from a Technology Readiness Level (TRL) of 3 through TRL 6.

Solar sail propulsion uses sunlight to propel vehicles through space by reflecting solar photons from a large, mirror-like sail made of a lightweight, reflective material. Because the Sun supplies the necessary propulsive energy, solar sails also require no onboard propellant, thus reducing payload mass. The NASA Science Mission Directorate Earth-Sun Systems Division's Draft Heliophysics Roadmap<sup>1</sup> has identified a number of missions that can be enhanced by solar sails, as shown in Figure 1, Heliophysics Mission Roadmap. For example, the continuous photonic pressure provides propellantless thrust to hover indefinitely at points in space (e.g. Heliosphere/L1) or conduct orbital maneuver plane changes (e.g. Solar Polar Imager - SPI) much more efficiently than conventional chemical propulsion. Eventually, a solar sail might propel a space vehicle to tremendous speeds—theoretically much faster than any present-day propulsion system - to reach interstellar space and explore the heliopause (e.g. Inter Stellar Probe - ISP).

Solar Sail Propulsion (SSP) is one of ISPT's three high priority investment areas, with the objective of near term verification and development of solar sail system level technology through ground testing and the development of subsystems, operations tools and computational models. NASA's Science Mission Directorate (SMD) funded research based on the results of peer reviewed proposals submitted to Topics in the Research Opportunities in Space Science (ROSS) of NASA Research Announcements (NRA). Table 1 lists the major SSP solicitations that were conducted under two ROSS NRA's (referred to as Cycle 1 and Cycle 2) and several smaller tasks issued to various NASA Centers as Directed Tasks. The SMD intends that space science solicitations should be guided

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\* Systems Engineer, Instrument & Payload Systems Department/EI61, Member AIAA

† Solar Sail Technical Area Manager, In-Space Propulsion Project Office/VP51, Member AIAA

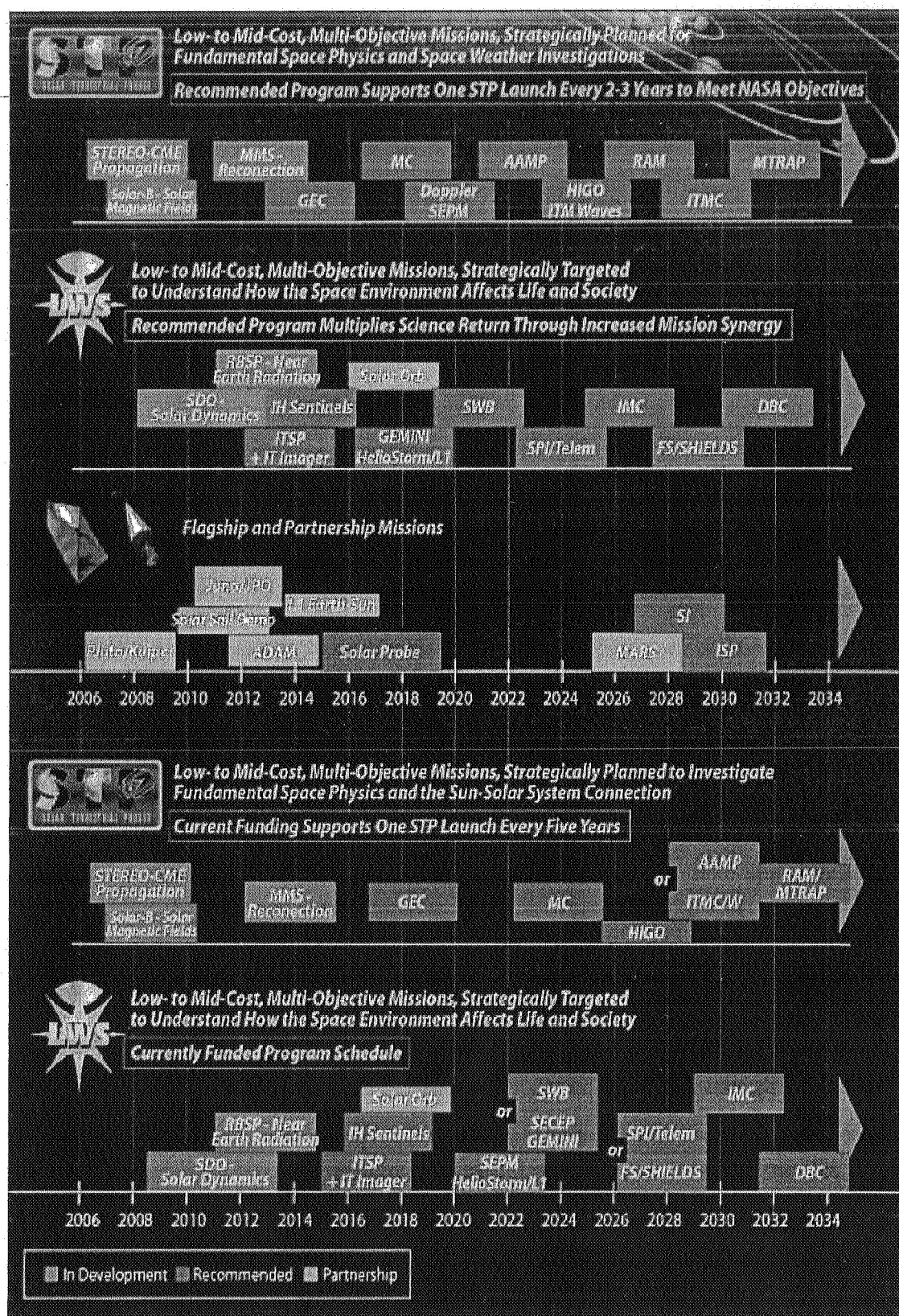


Figure 1: Heliophysics Mission Roadmap

<b>ROSS CYCLE 1 TASKS</b>		
<b>Name</b>	<b>PI</b>	<b>Status</b>
Scalable Solar Sail System (S <sup>4</sup> ) Ground Demonstration	AEC	Completed
Bringing an Effective Solar Sail Subsystem to TRL 6 Ground Demonstration	L'Garde	Completed
Solar Sail Spaceflight Simulation Software (S5)	JPL	Completed
<b>ROSS CYCLE 2 TASKS</b>		
Optical Diagnostics System for Solar Sails	NASA LaRC	Phase 1 completed; option not exercised
Advanced Computational Models and Software for Design and Simulation of Solar Sails Including Experimental Validation	NASA LaRC	Phase 1 completed; option not exercised
Development of a Low-Cost, Low-Mass, Low-Volume, and Low-Power Attitude Determination and Control System (L4-ADCS) and High-Fidelity Computational Models of Solar Sail Systems	Arizona State University	Completed
Laboratory Characterization of Candidate Solar Sail Material	NASA MSFC	Completed
Advanced Manufacturing Technologies for Solar Sails using Processes Developed Specifically for Production of Ultra-thin Solar Sail Materials for Near, Mid and Far Term Space Science Missions	SRS Tech	On going
Structural Analysis & Synthesis Tools for Solar Sails	JPL	Phase 1 completed; option not exercised
<b>DIRECTED TASKS</b>		
Smart Adaptive Structures	NASA MSFC	On going
Sail Charging	NASA MSFC/JPL	Completed
Long duration materials test	NASA MSFC	On going

**Table 1. ROSS NRA and Directed Tasks**

by input from the technology community. In the ISPT, and this is best achieved through the periodic convening of Technology Assessment Groups (TAGs). The first ISPT Solar Sail TAG was held over two days in January, 2002<sup>2</sup>. The interest represented at the TAG included the highest priority solar sail subsystems and components as well as the technical experts in photogrammetry, testing of gossamer structures and modeling. The TAG participants formed discussion groups to define what ground based testing and tools were needed in order to advance the solar sail Technology Readiness Level (TRL). Figure 2 is the Solar Sail technology development roadmap that was synthesized from the discussion group worksheets and has been used by the SSP office to develop all of the subsequent research solicitations. TAG's held in March, 2004<sup>3</sup>, and September, 2005<sup>4</sup>, further refined the roadmap with the recommendation of an additional ground demonstration of 40 meters to verify manufacturability and scalability of design, and provided an avenue for feedback from the PI's on the status of their work. The 2005 TAG was also significant in that two days were allocated for the Cycle 1 PI's to report the results of the manufacture and testing of two 20 meter Ground System Demonstrations prior to the TAG general meeting.

## **II. ISTP Cycle 1 Solicitation**

### **A. System Level Ground Demonstration**

The first of two SSP research elements in the ISTP Cycle 1 called for a prototype solar sail system for ground testing that would be used to validate design concepts for: sail manufacturing, packaging, launch to

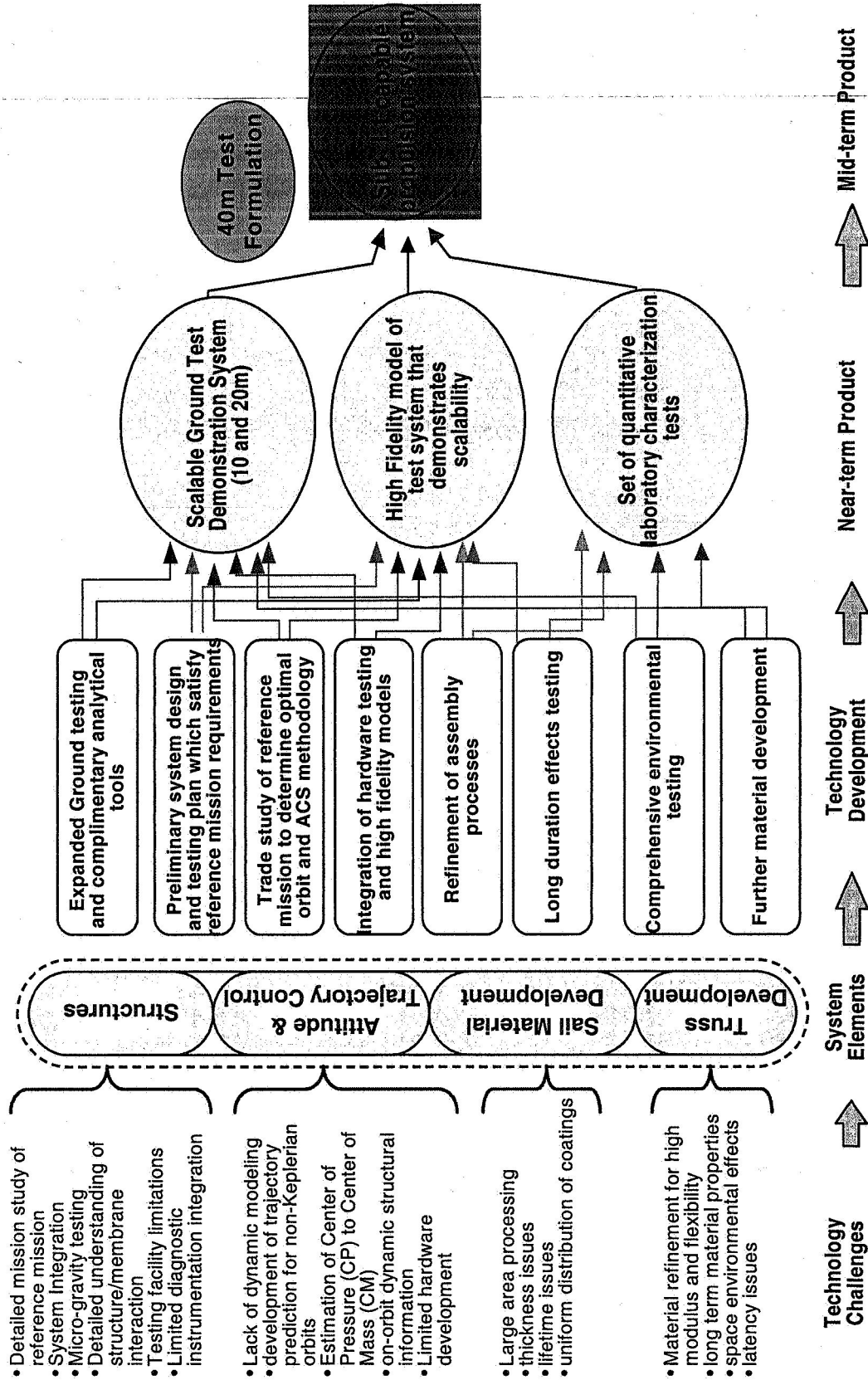


Figure 2: Solar Sail TAG Roadmap

space and deployment; attitude control subsystem function; and to characterize the structural mechanics and dynamics of the deployed sail in a simulated space environment. The solicitation called for a square sail configuration consisting of a reflective sail membrane, a deployable sail support structure, an attitude control subsystem, and all hardware needed to stow the sail for launch. In addition this system was required to meet the characteristics given in Table 2, columns 1 and 2. A sub-L1 solar monitoring mission concept was also provided as a reference mission for guidance in design and scalability issues, and is summarized in Table 3.

SSP awarded ground demonstration contracts to two companies that had proposed two separate types of technologies in order to achieve the project objective. ABLE Engineering Company's (now ATK Space Systems) proposed work based on their prior New Millennium Program (NMP) ST-7 proposal, incorporating their rigid coilable boom, an articulating boom attitude control system (ACS) subsystem and partner SRS' CP1 sail membrane. L'Garde Inc. proposed work based on the experience they gained on a NMP ST 5 proposal and as the sail provider for Team Encounter, incorporating their inflatable and sub-Tg rigidizable boom, a control vane based ACS and Mylar for the sail membrane. The parallel testing and development of these two system level demonstrations that have varied technologies in the three major components removed the risk to this technology development if one provider encountered an unrecoverable failure. The system level ground demonstration work was divided into three phases. A six month concept refinement phase was completed in May, 2003. During this Phase, the two teams provided analysis of their system's performance when scaled to the Design Reference Mission and a preliminary test plan for the following two twelve-month phases. The twelve-month hardware development phase began in June, 2003. In this phase both teams built and tested components and subsystems, with ATK concentrating on a single 10-meter quadrant and L'Garde developing a 10-meter square sail. The most comprehensive of these tests occurred in the middle of 2004 when the respective teams deployed their integrated subsystem in the LaRC 14-meter vacuum facility (ATK) and the 30-meter vacuum chamber at Glenn Research Center's Plum Brook Space Power Facility (L'Garde). Following a successful second phase the teams culminated their work in a twelve-month system verification phase. In this phase both teams built and tested fully integrated 20-meter sail systems that included a launch packaging container, and operational ACS subsystems. In the middle of 2005, the respective teams tested their system in the Plum Brook Facility under a high vacuum and appropriate thermal environment, as well as subjecting their systems to launch vibration and ascent vent tests. Figures 3 and 4 show the 20-meter deployed systems at the Plum Brook Facility. Table 2, columns 3 and 4 summarizes the final metrics achieved by ATK and L'Garde with their 20-meter systems. Since these sails represent the largest systems that will be tested in a vacuum chamber on the ground, a significant effort was made to collect static and dynamic data on the sails and booms with approximately 400 Gb of data collected, primarily raw photogrammetry data. Technical descriptions of work being performed by AEC<sup>5, 6, 7, 8</sup> and L'Garde<sup>9, 10, 11</sup> on the 20-meter GSD can be found in the respective team's papers.

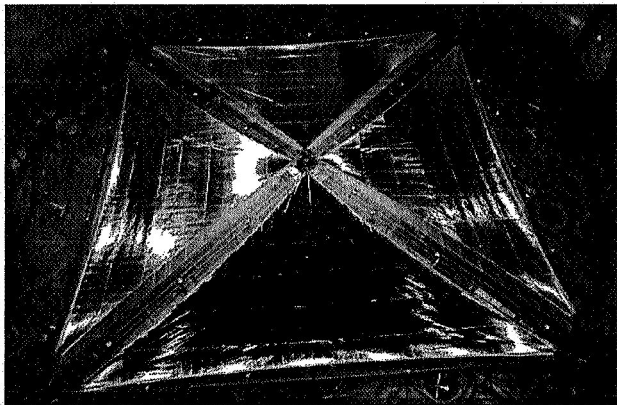


Figure 3. ATK 20 meter SGD

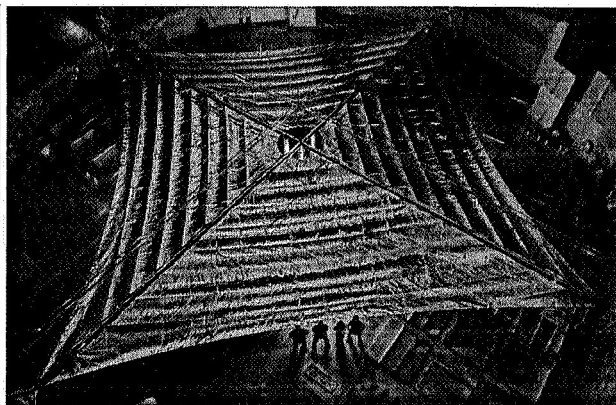


Figure 4. L'Garde 20 meter SGD

METRIC	RFP	ATK	• L'GARDE
<b>Dimensions:</b>	20 meters x 20 meters or greater	<ul style="list-style-type: none"> <li>• 20-m system with flight like central structure</li> <li>• 4 sails scaled from 80m</li> <li>• Truncated 80m masts</li> <li>• Central structure scaled from 40-m</li> </ul>	<ul style="list-style-type: none"> <li>• 19.5 m due to Plumbrook</li> <li>• 1 subscale TVCAD vane</li> <li>• Non-flight central structure scaled for 100m system</li> <li>• Sails and mast truncated 100m system</li> </ul>
<b>Sail Subsystem Areal Density</b>	< 20 g/m <sup>2</sup> (scalability to 12 g/m <sup>2</sup> for 104 m <sup>2</sup> )	<ul style="list-style-type: none"> <li>• 112 g/m<sup>2</sup> - includes spacecraft bus structure, ACS, power, instrument boom</li> <li>• scaled to 11.3 g/m<sup>2</sup> for 100m design and no payload</li> </ul>	<ul style="list-style-type: none"> <li>• 30 g/m<sup>2</sup> - includes ACS (4 vanes calculated), central structure dropped</li> <li>• scaled to 14.1 g/m<sup>2</sup> with 50kg payload and 41.4kg bus</li> </ul>
<b>Stowed Volume</b>	< 0.5 m <sup>3</sup> (scalability to 1.5 m <sup>3</sup> for 104 m <sup>2</sup> )	<ul style="list-style-type: none"> <li>• 0.9 m<sup>3</sup> scaled to 1.5 m<sup>3</sup> for 100m design</li> </ul>	<ul style="list-style-type: none"> <li>• 2.14 m<sup>3</sup> scaled to 1.04 m<sup>3</sup> for 100m design</li> </ul>
<b>Thrust Vector Turning Rate about roll axis:</b>	> 1.5°/hr	<ul style="list-style-type: none"> <li>• &gt; 35° maneuver in 2 hrs</li> </ul>	<ul style="list-style-type: none"> <li>• 63°/hour (.0175°/sec)</li> </ul>
<b>Effective Sail Reflectance</b>	> 0.75	<ul style="list-style-type: none"> <li>• 92% over solar spectrum</li> </ul>	<ul style="list-style-type: none"> <li>• 85.9</li> </ul>
<b>Anti-sunward Emissivity</b>	> 0.30	<ul style="list-style-type: none"> <li>• 0.30 for 3 micron film</li> </ul>	<ul style="list-style-type: none"> <li>• 0.40</li> </ul>
<b>Membrane Characteristics</b>	space-durable, tear-resistant, designed for 1 year in the near-GEO environment	<ul style="list-style-type: none"> <li>• ~2 micron CP1 with 1000 A of aluminum on front, bare CP1 on back of sail. All materials have space flight heritage.</li> </ul>	<ul style="list-style-type: none"> <li>• 2 micron Mylar with 1000 A of aluminum on front and 200A blackened chromium on back</li> </ul>
<b>System Flatness</b>	Effective for Propulsion	<ul style="list-style-type: none"> <li>• 3-point quadrant support with shear compliant border to insure a flat sail, with a proper stress level to obtain local flatness</li> </ul>	<ul style="list-style-type: none"> <li>• Stripped net loss ~ 2 %</li> </ul>
<b>ACS</b>	3-axis, minimize propellant usage	<ul style="list-style-type: none"> <li>• Sliding trim control mass on truss and tip bars to pinwheel quadrants for roll. Micro PPT backup</li> </ul>	<ul style="list-style-type: none"> <li>• Totally propellantless using four tip vanes</li> </ul>

Table 2. Cycle 1 System Level Ground Demonstration Reporting Metrics

#### B. Solar Sail Integrated Software Tools

The second of two SSP research elements in the ISTP Cycle 1 called for a set of integrated simulation tools to predict the trajectory, maneuvers, and propulsive performance of a solar sail during a representative flight profile. The solicitation encouraged that these tools should be able to be integrated into an optimal GNC subsystem on a future flight mission. In addition, the tools were required to be applicable to a solar sail mission of characteristics given in Table 3 and incorporate the following analytical models:

- Solar radiation pressure acting on the sail as a function of sail orientation and distance from the Sun.

- Disturbance forces acting on the sail such as gravitational torques and thermal deformation of the support structure.
- Orbital mechanics
- Sail structural dynamics
- Attitude control system dynamics
- Navigational sensors

The Solar Sail Spaceflight Simulation Software (S5) incorporated a six month Phase 1 that was completed in September, 2003, with Phase 2 completed in July, 2004, and Phase 3 completed in February, 2006. At the end of Phase III, of the 173 requirements specified in the S5 Software Requirements Document, 66 were fully implemented and integrated into the S5 system and 50 were partially integrated into the system or fully implemented in a standalone code. See reference 12 for a discussion of the S5 software and recent validation efforts.

Launch Mass (kg)	Payload Mass (kg)	Payload Power (W)	Total Power (W)	TM Dish (m)	TM Band	TM Rate (Kb/s)	S/C Dia (m)	Launch Vehicle
250	50	100	750	1.5	X	100	<2.3	Delta 2425-9.5

**Table 3. Design Reference Mission**

### III. Cycle 2 Task

#### A. Optical Diagnostic System

The overall objective for this task is the development of an Optical Diagnostic System (ODS) to TRL 6 for a solar sail. Possible requirements for the ODS included observation of the sail deployment and monitoring of the health and integrity of the sail during and after deployment. After solar sail deployment, the ODS would be available to provide shape and vibration measurements adequate to infer the stress state of the solar sail by aid of computational structural models which could then feed real time into a closed loop spacecraft guidance and control system. The initial six-month base period included concept development preceded by definition of the goals, priorities, and requirements for the ODS<sup>13</sup>. It was determined that continuous real-time integration with the guidance system was not necessary due to the quasi-steady-state nature of solar sail operations. In addition, studies by Zeiders<sup>14</sup> and Ewing<sup>15</sup>, showed the relative insensitivity of the thrust vector magnitude and direction to sail billow. The conceptual design process identified a number of significant challenges to on-orbit photogrammetry including significant weight, power, and data requirements for instruments and support structures for camera clusters, achieving sufficient image contrast, integrating targets into the sail membrane, and considerable software development needs. The concept development activities were conducted in parallel with the development of the ground test capability for the solar sail demonstrator hardware. A developmental test of a L'Garde inflatable boom in a thermal vacuum chamber at Goddard Space Flight Center, as well as tests on smaller sail quadrants<sup>16</sup>, provided an opportunity to familiarize researchers with cameras, analytical tools, and test operations. Building on this experience and adding capabilities for dynamic excitation and laser vibrometry, imaging, and a "truth" instrument, the ATK 10-meter demonstrator testing was performed in the 16-meter vacuum chamber at LaRC. These activities formed the foundation for the test methods and instrumentation employed in the final 20-meter demonstrations tests. An exceptional team of photogrammetry experts from LaRC, working in conjunction with the contractor test teams, were successful in acquiring both static and dynamic deflection data in a number of various thermal and vacuum conditions and system configurations despite tremendous difficulties that arose. For example, condensate "rain" fell on the test article as the huge Plum Brook chamber was pumped down, causing boom tip positions to change so much that complex, remotely operated, adjustable instrument platforms had to be devised. A tremendous volume of data was required to provide high resolution measurements over 400 square meters of area and data collection was made difficult by the clean aluminum walls and floor of the chamber which provide little natural contrast to the aluminized sails. Finally, the cost of operations in such a large chamber is not inconsiderable. The teams were constantly under the gun to debug problems, acquire data, and assess data quality quickly with limited hands on the equipment and only a few pump-downs allowed. The difficulty of photogrammetry was not insurmountable, but it

did indicate the challenges identified in the conceptual design phase were real. Combined with a better understanding of the lack of a need for on-orbit photogrammetry, the further development of a flight system was not pursued.

#### **B. Advanced Computational Methods**

The TAG had expressed concern that conventional finite element models might be inadequate to evaluate solar sails. Therefore, a three pronged attack on the structural design issue was pursued. The first attack relied on the prime contractors to apply standard practices using the existing state of the art. As part of the Ground System Demonstrations, Finite Element Models (FEAs) were created by LaRC, ATK and L'Garde of the 10-meter systems using both COTS and custom software. These models didn't always converge and were computationally intensive, but no more so than is experienced in typical spacecraft design. The purpose of this task was to create methods/algorithms/techniques that improved the conventional FEA of the membranes, booms, and other subsystems. Several methods were identified, but the option phases to complete and validate them were not funded due to the success of the prime contractors in modeling the 20-meter systems with conventional techniques, thus lowering the priority of this task below the level of the available funding.

#### **C. Structural Analysis & Synthesis Tools**

The third prong in the attack on the structural analysis issue involved the ground-up development of unconventional modeling techniques. Techniques considered included Direct Transfer Function Modeling (DTFM) and Parameter Variation Processing (PVP). The overall objectives for this task were completion of DTFM modeling/analysis methods for long booms, completion of capability to evaluate effects of imperfections, completion of PVP method for analyzing wrinkled membranes, and completion of test/analysis correlation by using existing test data. As in the above task, this effort was terminated prior to completion due to success using conventional modeling methods with the 20-meter systems and a lack of funding.

#### **D. Lightweight Attitude Control System**

The objectives of this two-year project are: (i) to design, integrate, and test a sail attitude control system (SACS) employing a two-axis gimbaled control boom, and also (ii) to develop a high-fidelity, multi-flexible body model of ATK's solar sail for the purpose of validating a thrust vector control (TVC) concept employing a two-axis gimbaled control boom. One of the major findings from this study was that the two axis gimbaled control boom was not a mass efficient method of controlling a sail sail<sup>17</sup>. A more efficient method was derived based on an offset mass moved along the booms by a clothesline-like apparatus to control pitch and yaw and rotating stabilizer bars at the sail tips to pinwheel the sail quadrants for roll control. This finding led to a major redesign of the ATK 20-meter hardware to accommodate the new TVC concept. An attitude determination and control block diagram was derived to present the application/integration of the inertial stellar compass with a range of ACS options from cp/cm offset to pulsed plasma microthrusters<sup>18</sup>. Although 95% of the work is complete<sup>19</sup>, the contract is currently open to enable further developments from other ASU research efforts to be incorporated.

#### **E. Characterization SS Material**

The purpose of this task was to conduct laboratory characterization of several candidate solar sail materials. The space radiation and micrometeoroid environments for 1.0 (Heliostorm) and 0.5 (SPI) astronomical units missions were defined and candidate materials were tested against these radiation and meteoroid environments. Through a series of learning tests, the sample hold down designs was optimized and a flexure test developed. Several samples of the SRS and L'Garde membrane materials were tested by subjecting them to gigarad levels of radiation – in simulations of long duration solar wind mission types<sup>20</sup>. While some of the samples showed significant levels of degradation in mechanical strength, solar sail loading is so low, very little strength is needed.

#### **F. Advanced Manufacturing Technologies for Solar Sails**

The purpose of this task was to investigate and develop an integrated approach to ultra-thin film solar sail manufacturing. The focus was on improving coating processes and technologies; developing sail seaming technologies for large monolithic sails; providing an integrated approach to membrane coating, acceptance, assembly and integration; and integrating future improvements (such as electrospun nanofibers for ripstop enhancement without added mass and the addition of carbon black nanotubes to the sail backside to increase emissivity)<sup>21</sup> into the process. The final results of this two-year effort are the development of a scroll coating system,

the development of coating capabilities of less than 2.5 microns, and the development of a membrane seaming system able to form monolithic sails with coatings at least as thin as 2.5 microns.

#### **IV. Directed Tasks**

##### **A. Smart Adaptive Structures**

In order to mature the TRL of solar sail propulsion, advancements must be made in the pointing and dynamical control of these large space structures. This task's objective was to develop and verify structural analytical models, develop structural scaling laws and develop adaptive control laws for solar sails to be verified on a >30-meter vertically supported boom. In the summer of 2006, a closed loop boom controller will be demonstrated.

##### **B. Charging in Space Environment**

Due to two extreme characteristics of future Solar Sail missions, the large surface area of the Sail and the long duration of potential missions, typical spacecraft charging issues will be exacerbated. The purpose of this task was to characterize charged particle environments for analyzing solar sail charging in the solar wind and at geostationary orbit and to model surface and internal electric fields and potentials for solar sails using existing spacecraft charging models. Solar sail materials were tested in simulated charging environments to determine permeability and charge retention properties. The task was completed March 1, 2006. A significant finding was that there will be very little charging of the sail surfaces, ~10 volts as a worst case in sunlight. The study found that problems arise if the sail material backing is non-conductive or electrically decoupled from the front surface. In that case, the shadowed back surface can reach potentials of -30 to -40 volts relative to the space plasma in the solar wind—on the order of arcing onset potentials. The solution is to make sure the sail material is conductive front to back and end to end if the sail is to be in geosynchronous orbit or in the auroral zone and be very careful with electrically isolated objects in the shadow of the sail.<sup>22</sup>

##### **C. Long Term Space Environmental Effects**

Critical to the development of Solar Sails is an investigation of space environmental effects on these large thin film materials and the edge support technologies. This task was related to the "Characterization SS Material" task above. The above task used accelerated dose levels over a shorter period of time to simulate the total dose of radiation received by a material for many years. The purpose of this task is to provide critical thermal, optical, mechanical, and surface data on large sails taking into account edge stresses and edge support technologies that can only be characterized using large size sails but not at accelerated levels. These resulting test data could be used to validate the accelerated dose test methodology regarding the durability of candidate sail material (embrittlement, optical, mechanical, surface, and thermal properties). This task was recommended by 2004 TAG.

##### **D. SRS Solar Sail Propulsion Evaluation Tool**

This sixteen-week study provides a better understanding of the impacts of non-ideal sail characteristics to support further solar sail development. This study is divided into three tasks. Task 1 is Integrated Optical Design Analysis (IODA) Software Modification to support solar sail propulsion analysis. The objective of the sail analysis model is to provide a detailed calculation of the thrust vector magnitude, direction, and center of pressure based on the predicted shape of the sail and the sail optical properties including reflectivity, emissivity, and specularity. The program will also calculate the torques applied to the vehicle using the thrust vector, center of pressure, and vehicle center of mass. Task 2 is for the development of models to characterize the total momentum transfer imparted to a sail element (including the contributions from thermal emissions and diffuse reflections). Task 3 is for software testing. This is to include at least one FEM to be used for testing the software, demonstration of the software using any additional NASTRAN or ALGOR FEM models provided, and delivery of a Beta test version of the modeling software for evaluation by government personnel.

#### **V. Other Tasks**

A number of other proposed tasks were submitted as directed task requests, solicited in later NRAs, and recommended by the TAGs. They were not funded for various reasons, but mostly as a consequence of prioritization of the available budget. These included a combined effects material test in which MSFC irradiated samples would be sent to Glenn Research Center and exposed to the solar simulator thermal vacuum chamber environments.

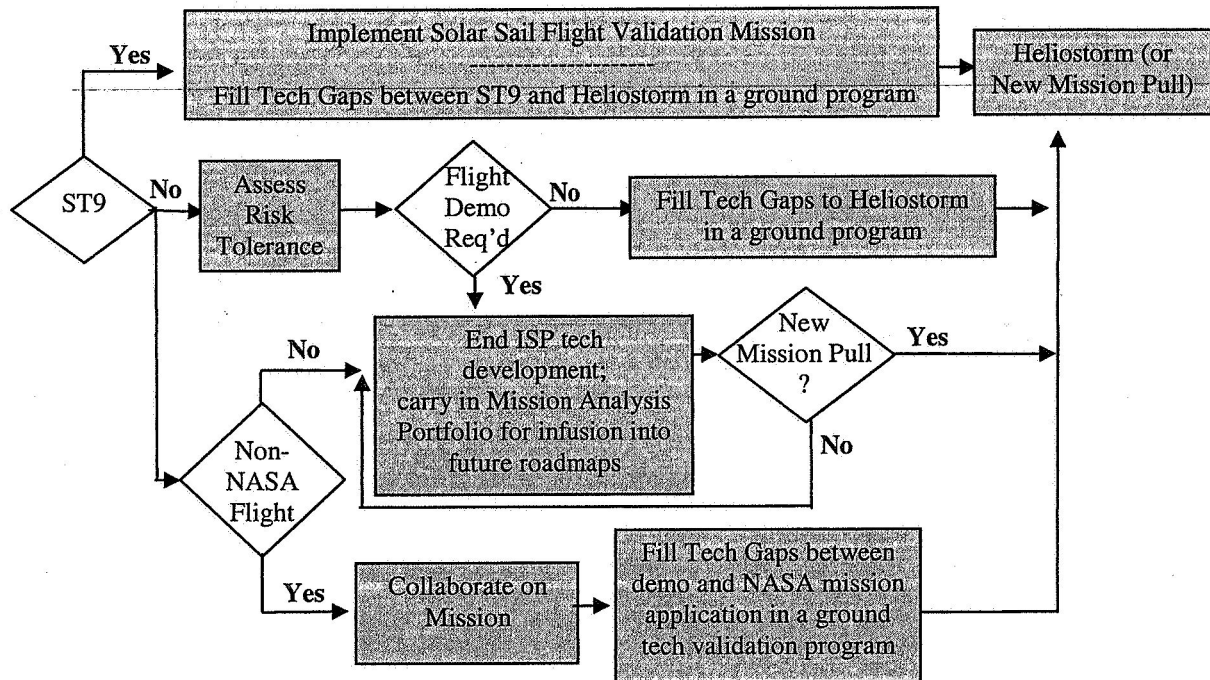


Figure 5. Solar Sail Decision Tree

Another task would create and organize a data base of known optical property data. Several interesting proposals were selected for direct measurement of thrust in a ground experiment.

## VI. Future Directions

The SSP Project approach of providing near term verification of solar sails through the development of system level technology using ground testing and the development of subsystems, operations tools and computational models has begun building a technological foundation that can be readily used by future programs (e.g., New Millennium Program) in their pursuit of providing space validation of this technology. As shown in Figure 5, the In-Space Propulsion Technology Program has developed a decision tree that lays out several potential paths to continue solar sail technology development based on the upcoming ST9 decision in late 2006. In so doing, this work will bring the technology to a readiness level such that it will minimize the exposure to risk of future flight programs.

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